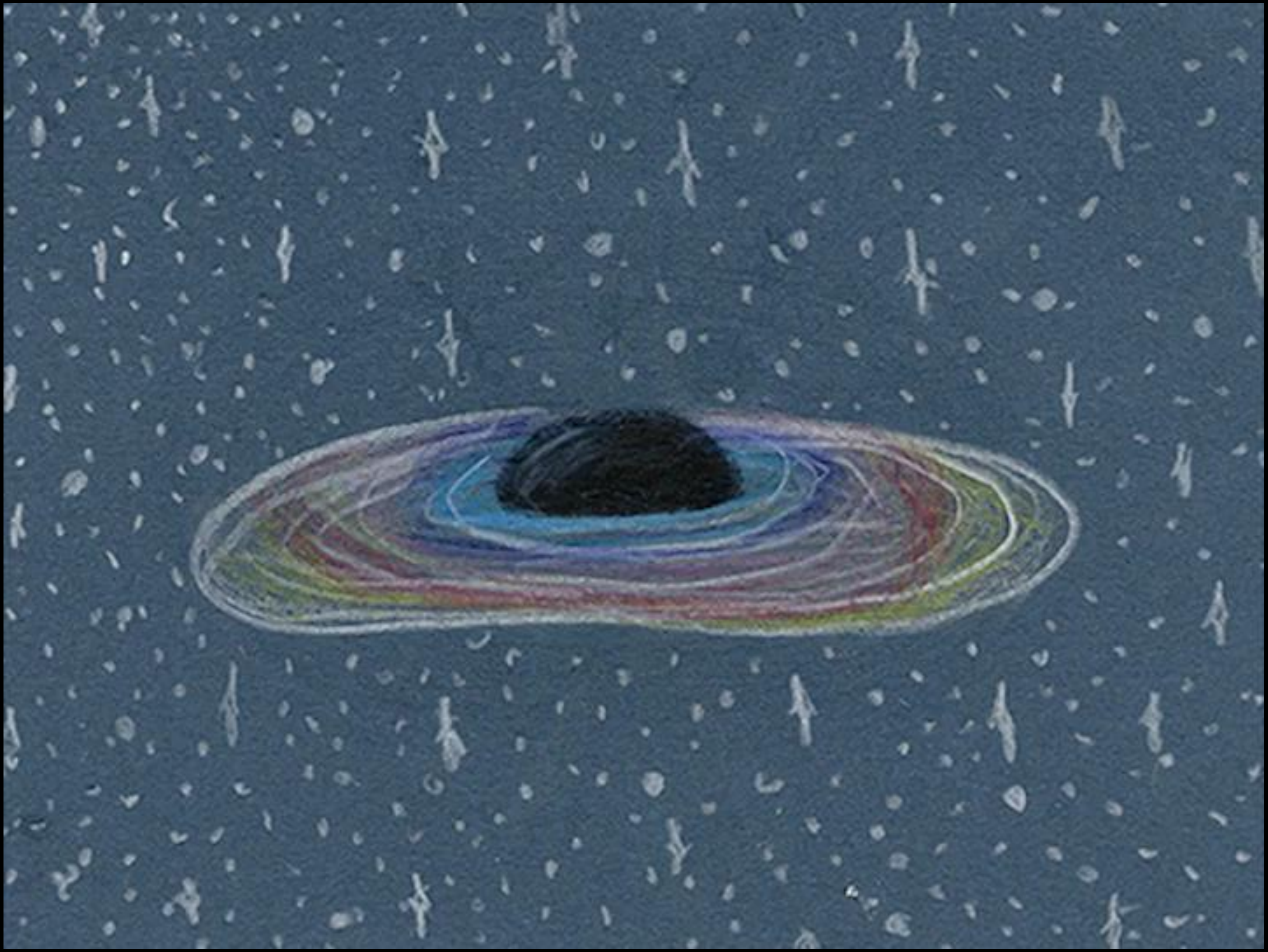
Black holes: the last frontier



TÉCNICO LISBOA

Vitor Cardoso

European Research Council
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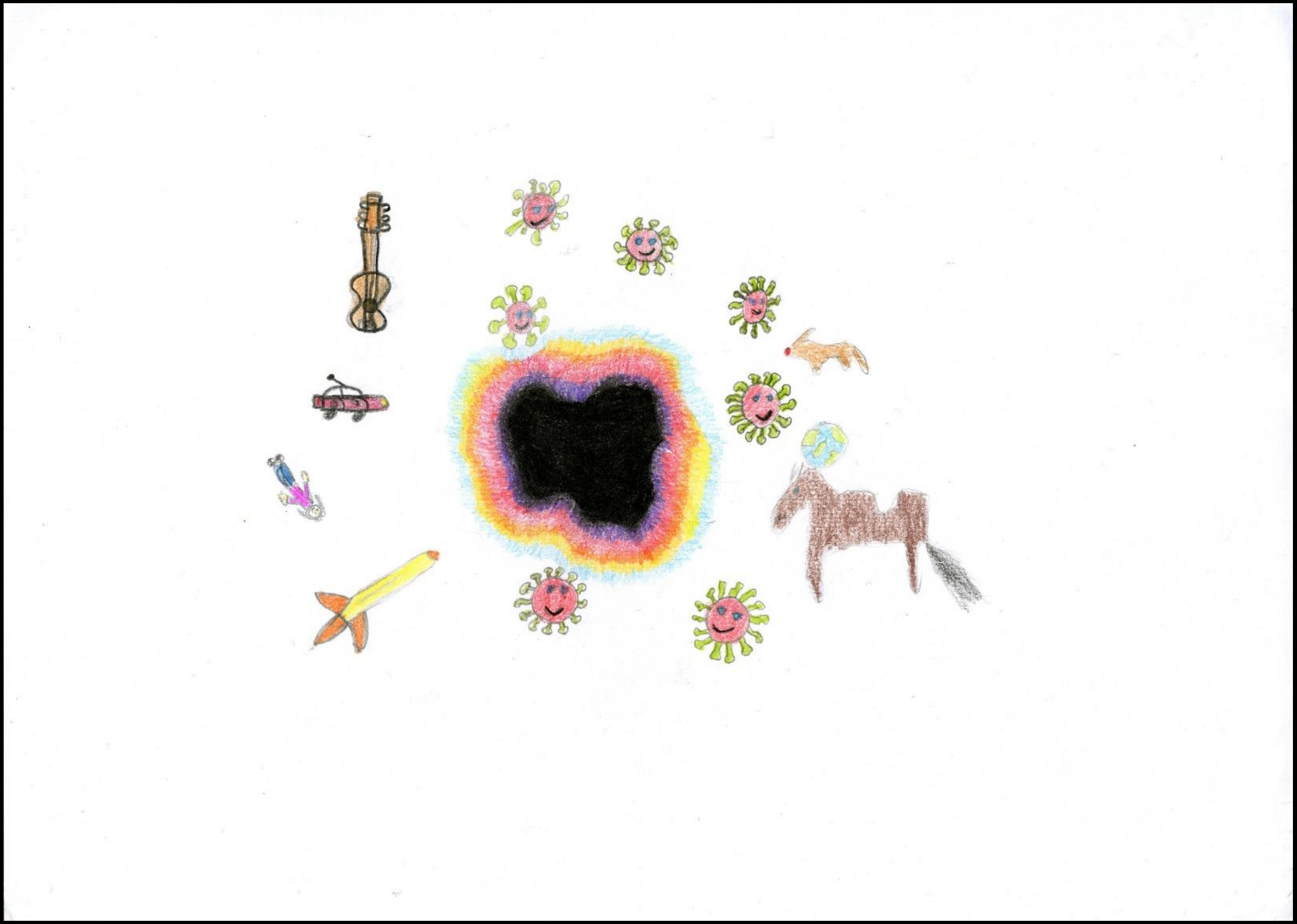
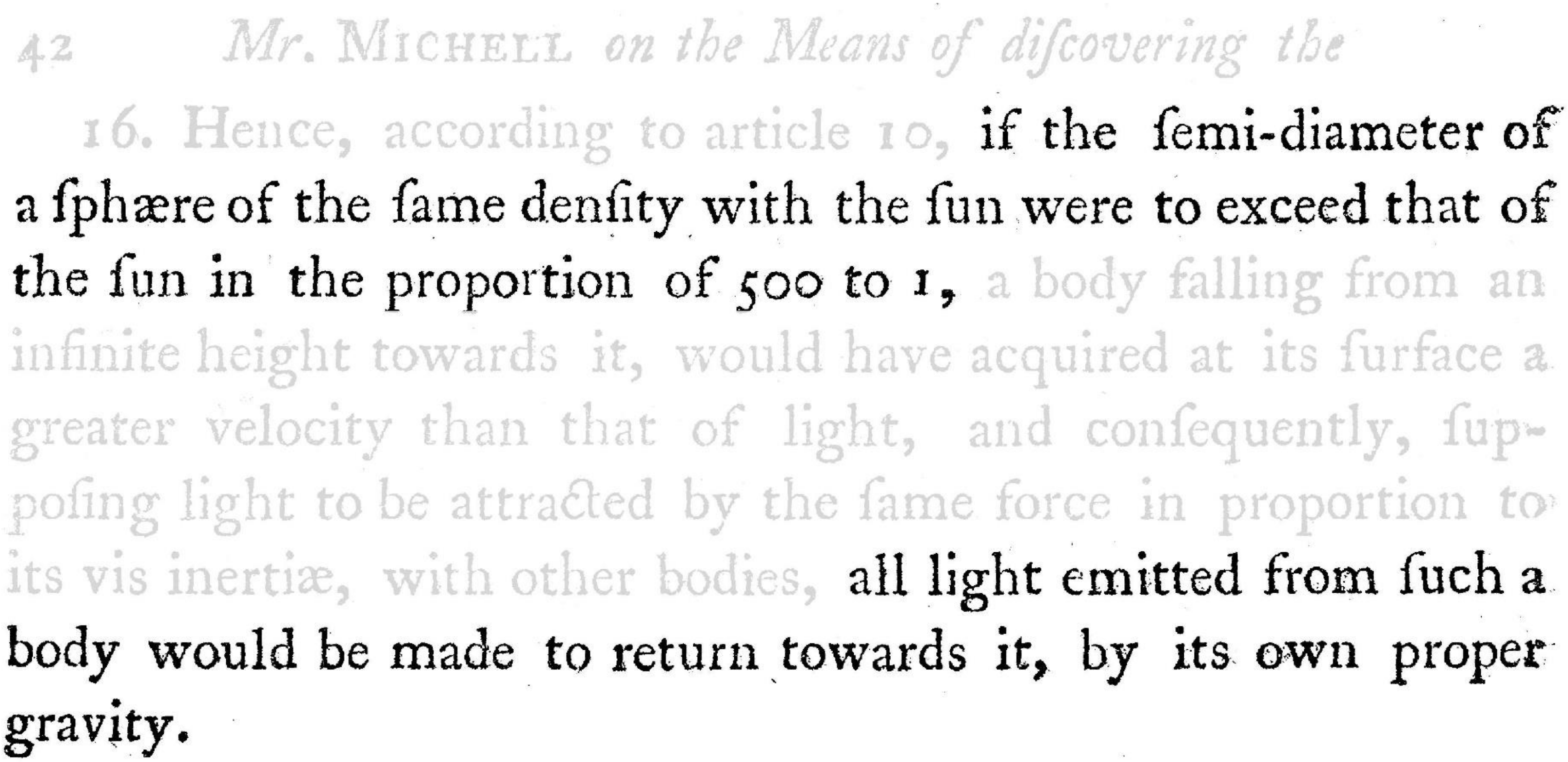


Sara Henriques, 7º-2, Escola Básica e Secundária Dr. Luís Maurílio da Silva Dantas
Câmara de Lobos, Madeira

Origins of the Classical Definition



42 Mr. MICHELL *on the Means of diſcovering the*

16. Hence, according to article 10, if the ſemi-diameter of a ſphære of the ſame denſity with the ſun were to exceed that of the ſun in the proportion of 500 to 1, a body falling from an infinite height towards it, would have acquired at its ſurface a greater velocity than that of light, and conſequently, ſuppoſing light to be attracted by the ſame force in proportion to its vis inertiæ, with other bodies, all light emitted from ſuch a body would be made to return towards it, by its own proper gravity.

"I made at once by good luck a search for a full solution. A not too difficult calculation gave the following result: ..."

K. Schwarzschild to A. Einstein
(Letter dated 22 December 1915)

Solution re-discovered by many others:

J. Droste, May 1916 (part of PhD thesis under Lorentz):
Same coordinates, more elegant

P. Painlevé, 1921, A. Gullstrand, 1922: P-G coordinates
(not realized solution was the same)

...and many others

Uniqueness: the Kerr solution

Theorem (Carter 1971; Robinson 1975; Chrusciel and Costa 2012):
A stationary, asymptotically flat, vacuum BH solution must be Kerr

$$
\begin{aligned}
ds^2 \quad &= \quad \frac{\Delta - a^2 \sin^2\theta}{\Sigma} dt^2 + \frac{2a(r^2 + a^2 - \Delta)\sin^2\theta}{\Sigma} dt d\phi \\
&\quad - \frac{(r^2 + a^2)^2 - \Delta a^2 \sin^2\theta}{\Sigma} \sin^2\theta d\phi^2 - \frac{\Sigma}{\Delta} dr^2 - \Sigma d\theta^2
\end{aligned}
$$

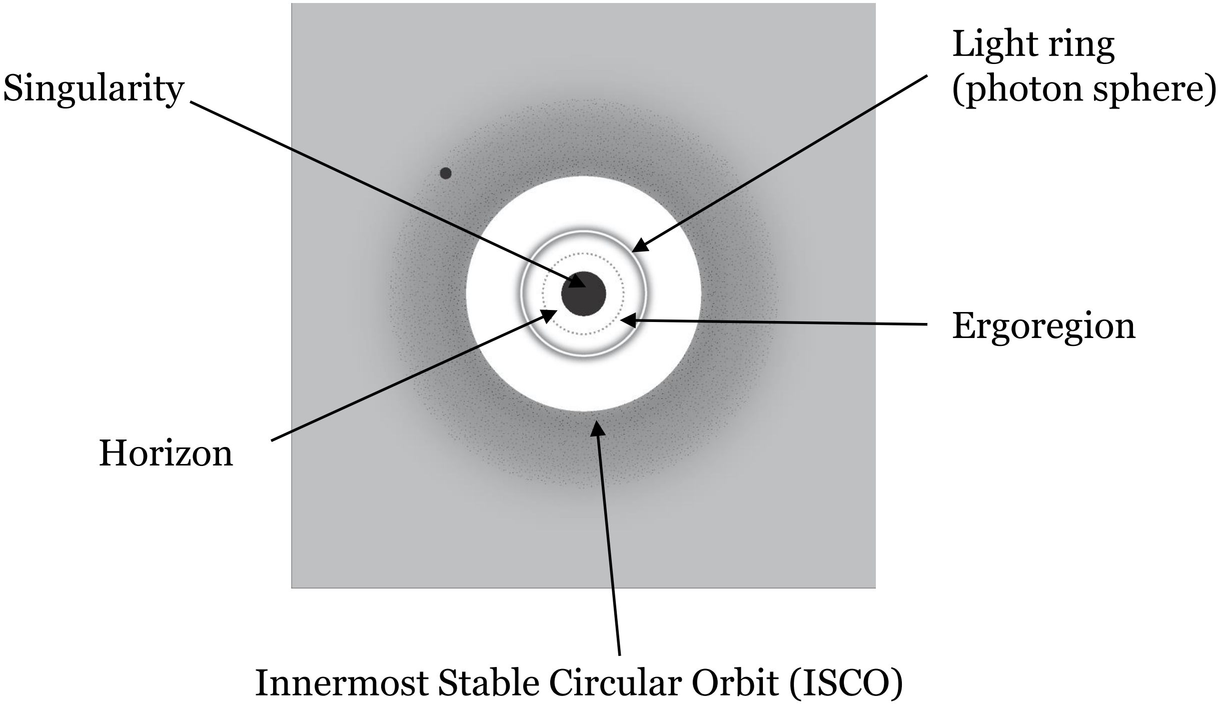
$$
\Sigma = r^2 + a^2 \cos^2\theta\,, \quad \Delta = r^2 + a^2 - 2Mr
$$

Describes a rotating BH with mass M and angular momentum J=aM, iff a<M

“In my entire scientific life, extending over forty-five years, the most shattering experience has been the realization that an exact solution of Einstein’s equations of general relativity provides the *absolutely exact representation* of untold numbers of black holes that populate the universe.”

S. Chandrasekhar, The Nora and Edward Ryerson lecture, Chicago April 22 1975

Black holes are black



Any evidence for existence of these features is welcome

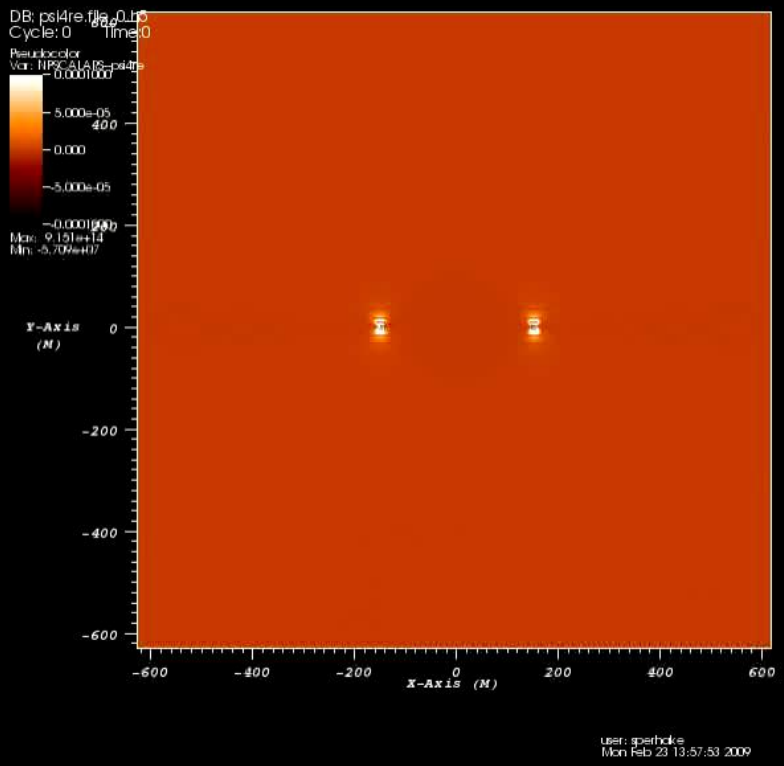
Cardoso & Pani, Living Reviews in Relativity 22: 1 (2019)

Image: Ana Carvalho

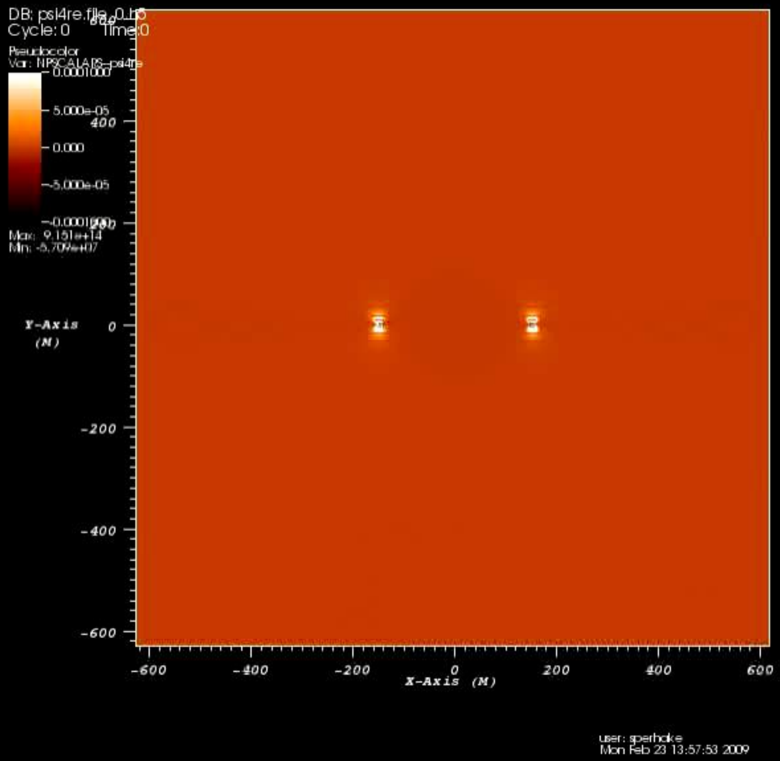
(Weak) Cosmic Censorship violations?

$$\frac{cJ}{GM^2} \leq 1 \qquad \text{or} \qquad a \leq M$$

Black holes have small angular momentum (very compact objects)



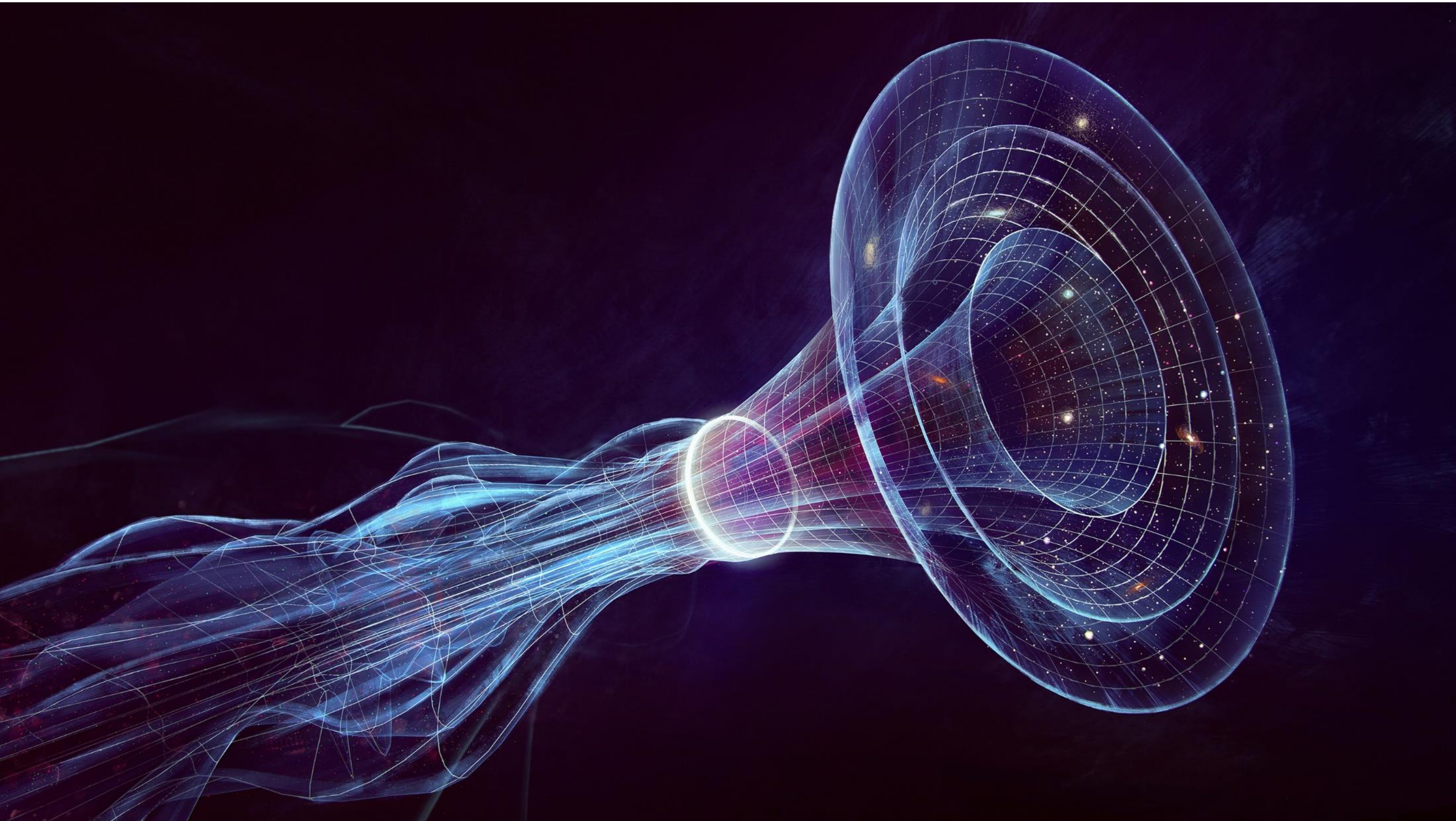
Sperhake + PRL103:131102 (2009)



Sperhake + PRL103:131102 (2009)

The inside story: (strong) Cosmic Censorship violations!

Poisson & Israel 1990; Cardoso+ PRL120 (2018) 031103



Energy source?

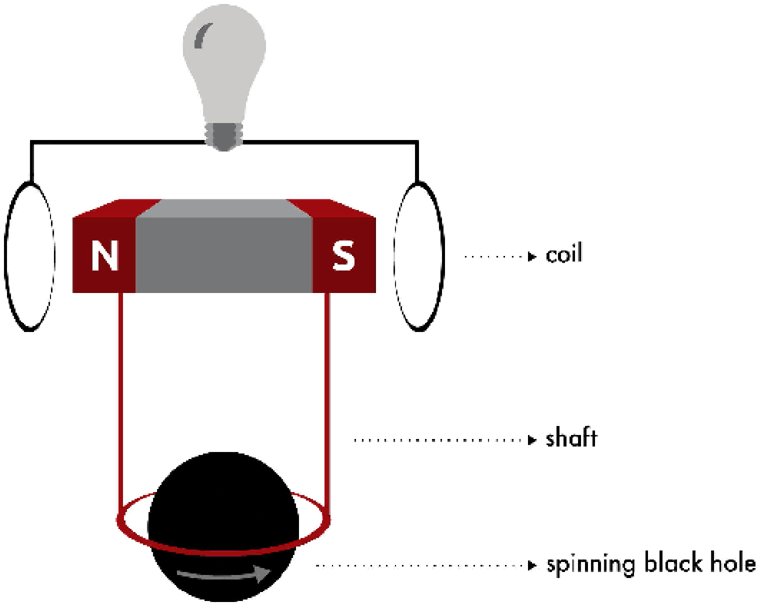


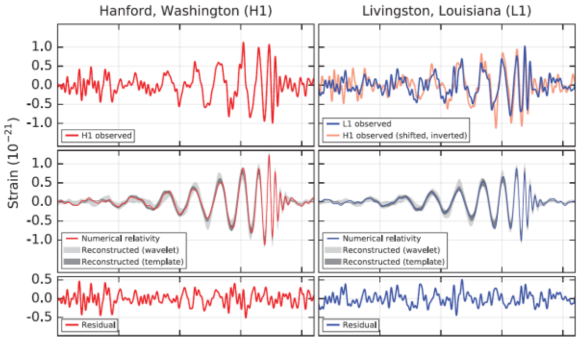
Image: Ana Carvalho

Brito, Cardoso & Pani, *Superradiance* (Springer-Verlag, 2020)

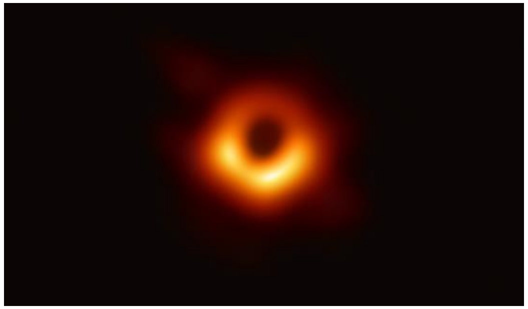
I only wish to make a plea for "black holes" to be taken seriously and their consequences to be explored in full detail. For who is to say, without careful study, that they cannot play some important part in the shaping of observed phenomena?

Penrose, Gravitational Collapse: the role of General Relativity (1969)

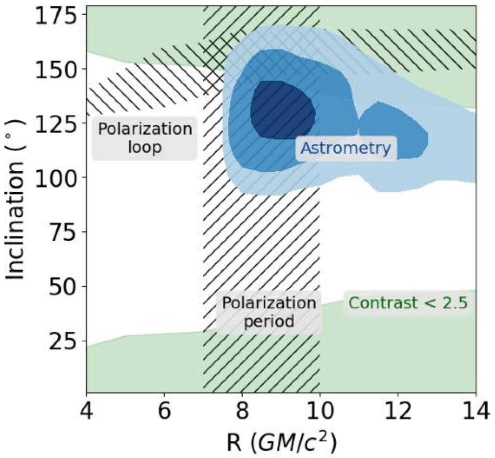
They exist! (?)



LIGO/Virgo Collaboration PRL116:061102 (2016)



EHT Collaboration ApJL 875: 1 (2019)



GRAVITY Collaboration AA 635: A143 (2020)

Fundamental questions

a. Is it a Kerr black hole? Can we constrain alternatives?

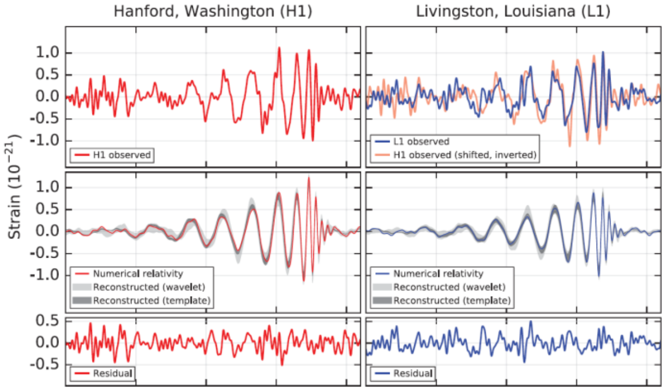
Berti+ PRL117: 101102 (2016); Cardoso & Gualtieri CQG33:174001 (2016)

b. Is the final - or initial - object *really* a black hole?

Cardoso+ PRL116: 171101 (2016); Cardoso & Pani, Nature Astronomy 1: 586 (2017)

c. Can GWs from BHs inform us on fundamental fields/DM?

Barack+arXiv:1806.05195; Brito+ PRL119:131101 (2017); Annulli+ PRD102:063022 (2020)



Answer requires understanding of theoretical framework, precise modelling, challenging simulations & challenging data analysis techniques

Inspiralling compact objects

$$\text{Binding Energy}: E_b = -\frac{GM\mu}{2L} + \text{other interactions}$$

$$\text{Quadrupole emission}: \dot{E} = -\frac{32}{5}\frac{G\mu^2 L^4 \Omega^6}{c^5} + \text{other emission channels}$$

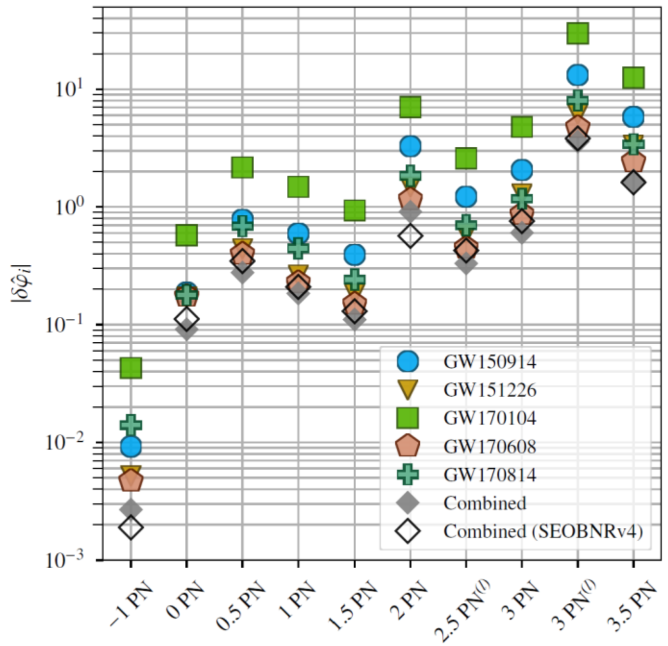
$$h(f, \text{pars}) = A(f, \text{pars}) e^{i\Psi(f,\text{pars})}$$

$$\Psi = \frac{3}{128}\left(G\mathcal{M}\pi f/c^3\right)^{-5/3}\left(\ldots + \underset{\substack{\uparrow \\ \text{Variation of G}}}{\alpha_{-4PN}x^{-4}} + \ldots + \underset{\substack{\uparrow \\ \text{Dipole moment} \\ \text{(electric charge)}}}{\alpha_{-1PN}x^{-1}} + 1 + \underset{\substack{\uparrow \\ \text{Graviton mass}}}{\alpha_{1PN}x} + \ldots\right)$$

$$x = (\pi M f)^{2/3}\,, \quad M = m_1 + m_2\,, \quad \nu = m_1 m_2/M^2\,, \quad \mathcal{M} = \nu^{3/5} M$$

M. Maggiore, Gravitational waves, Volume I

Parametrized tests



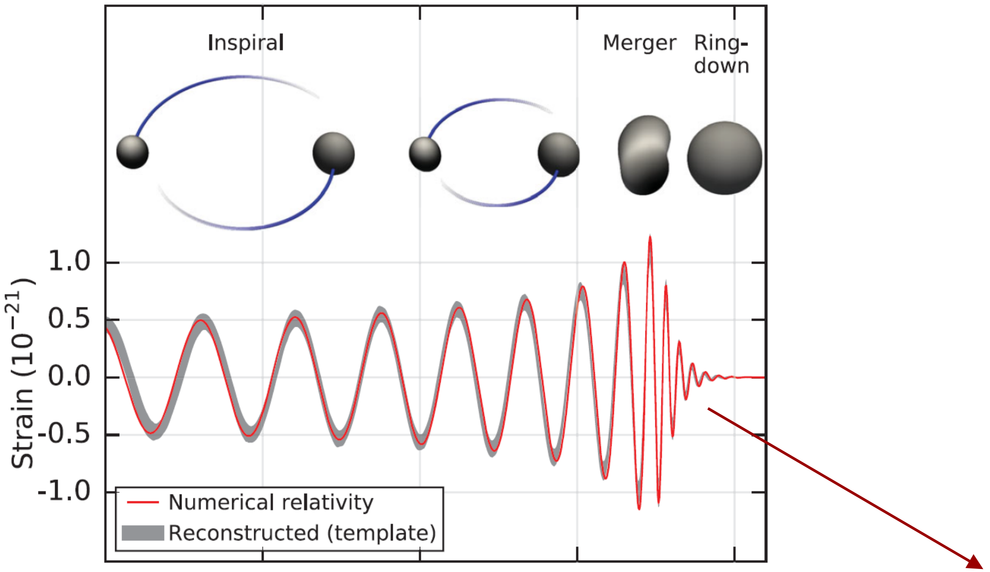
LVC arXiv:1903.04467; see arXiv:2010:14529 for latestevents

Any specific theory bound to affect all PPN parameters

Some of these - extra dimensions, varying-G, graviton mass, etc, derived with hand-waving arguments, blind to full theory

In other words, we need to know full waveform, and underlying theory

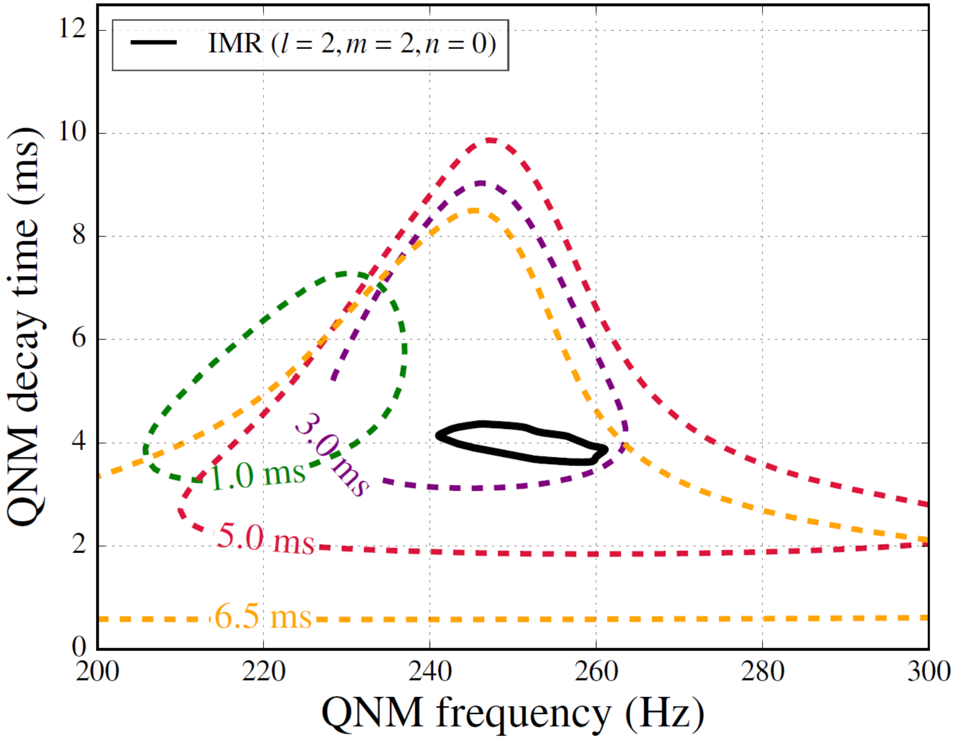
BH spectroscopy: testing the Kerr nature



Ringdown

$$h = \sum_k A_k e^{-\omega_I^{(k)} t} \sin\left(\omega_R^{(k)} t\right)$$

One and two-mode estimates



90% posterior distributions.

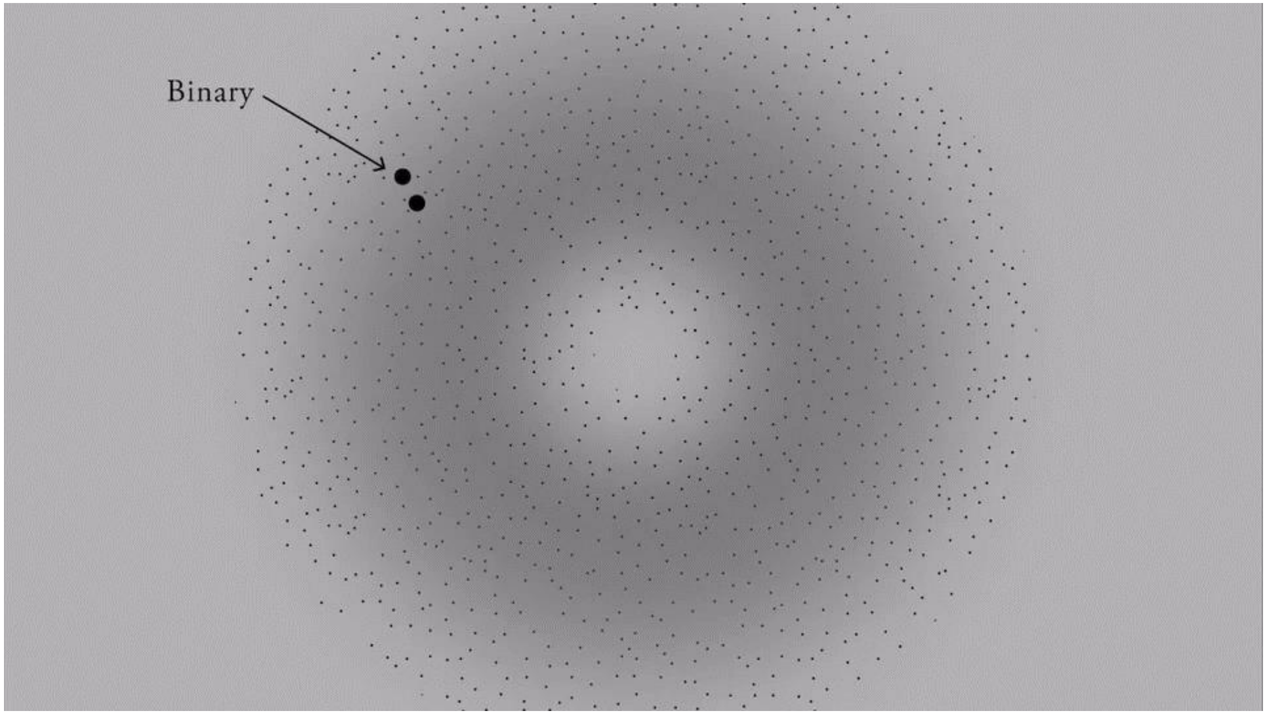
Black solid is 90% posterior of QNM as derived from the posterior mass and spin of remnant

LSC PRL116:221101 (2016); see Bhaibav+PRD97:044048 (2019); Isi+ PRL123:111102 (2019)
See also recent LIGO/Virgo analysis arXiv:2010.14529

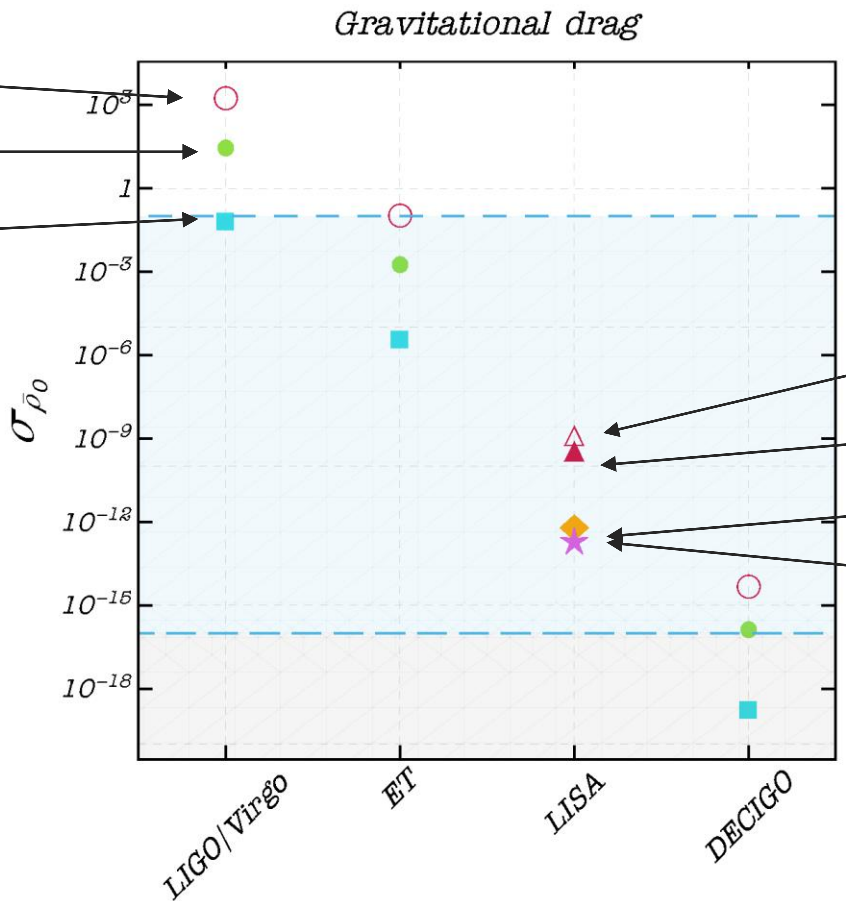
GWs and dark matter I

DM not strong-field phenomenon, but GW observations may reveal a “mundane” explanation in terms of heavy BHs.
Bird + PRL116:201301 (2016)

Inspiral occurs in DM-rich environment and may modify the way inspiral proceeds, given dense-enough media: accretion and gravitational drag play important role.
Eda + PRL110:221101 (2013); Macedo + ApJ774:48 (2013); Cardoso + arXiv 1909.05870; Kavanagh + arXiv 2002.12811; Annulli + arXiv 2009.00012



Small Compton wavelength: heavy DM



GW150914

GW170608

GW170817

IMRI

EMRI

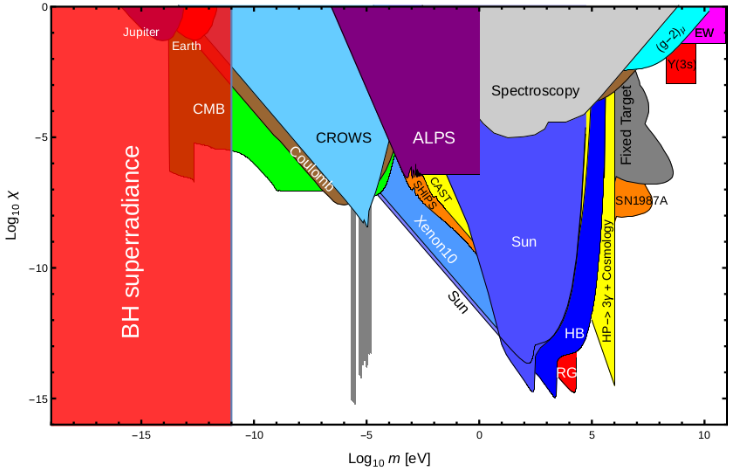
MBBH high spin

IMBBH low spin

Effect is -5.5 PN on GW phase

Cardoso & Maselli AA (to appear) arXiv 1909.05870
Also Eda + PRL 110 (2013) 221101; Macedo+ApJ774 (2013) 48; Annulli+ PRD102;063022 (2020)

DM II. Light fields



Cardoso+ 2018, adapted from Sigl (2017) and Jaeckel arXiv:1303.1821

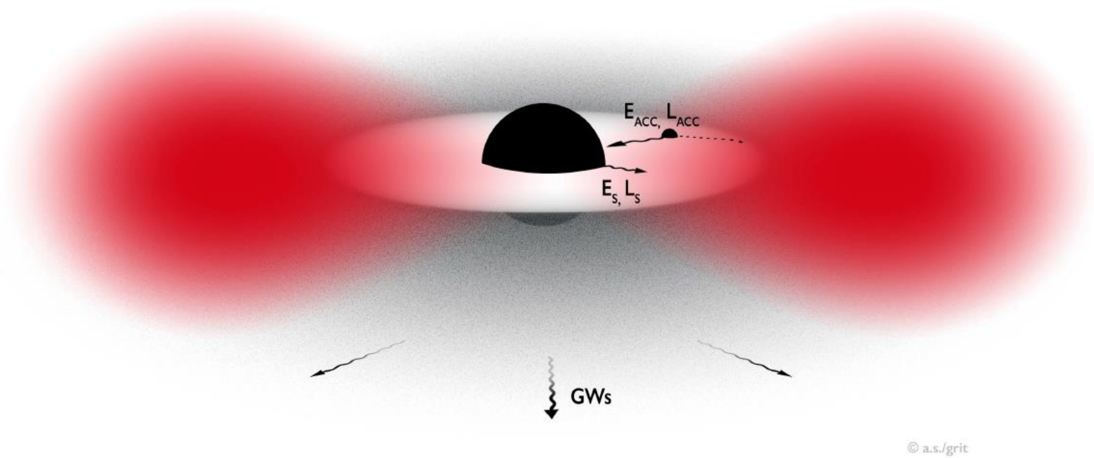
Interesting as effective description; proxy for more complex interactions; arise as interesting extensions of GR* *(BD or generic ST theories, f(R), etc)*

Bosons do exist (Higgs) and lighter versions may as well
Peccei-Quinn (interesting because not invented to solve DM problem), axiverse (moduli and coupling constants in string theory)

$$\mathcal{L} = \frac{R}{k} - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{2}g^{\mu\nu}\partial_\mu\Psi\partial_\nu\Psi - \frac{\mu_{\rm S}^2}{2}\Psi\Psi - \frac{k_{\rm axion}}{2}\Psi\ {}^{*}F^{\mu\nu}F_{\mu\nu}$$

...and one or more could be a component of DM. *D. Marsh, Phys. Repts. 2016*

Fundamental fields: particle detectors in the sky



$$\nabla_\gamma \nabla^\gamma \Psi = \mu^2 \Psi\,, \quad \nabla_\gamma F^{\gamma\nu} = \mu^2 A^\nu\,, \quad \nabla_\gamma \nabla^\gamma h_{\mu\nu} = \mu^2 h_{\mu\nu}$$

$$\Psi \sim e^{-i\omega t} Y_{lm}$$

$$\omega \sim \mu + i(m\Omega_H - \mu)(M\mu)^{4l+5+S}$$

$$S = -s, -s+1 \ldots, s-1, s$$

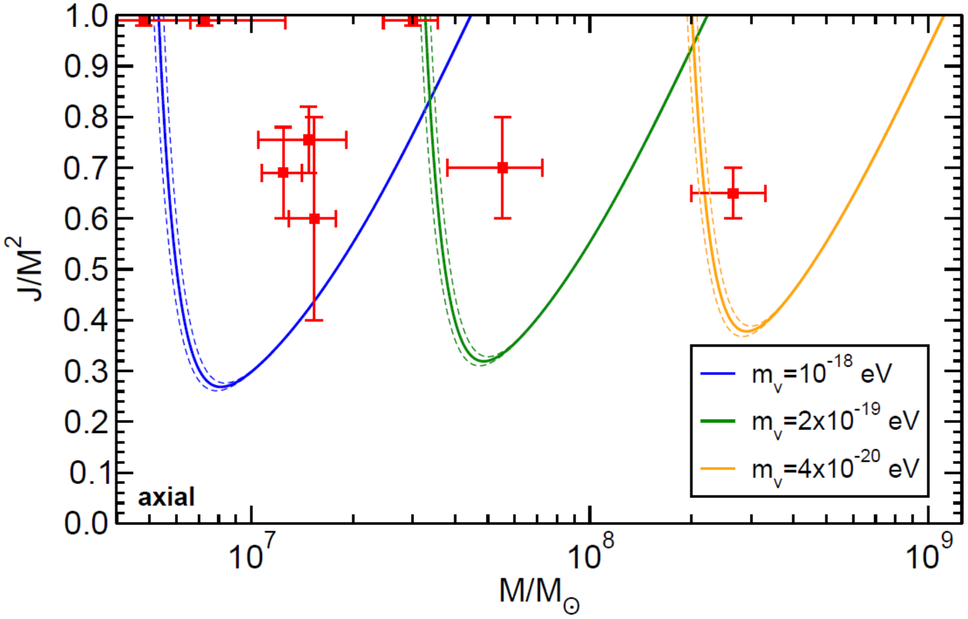
$$\tau \sim 100 \left(\frac{10^6 M_\odot}{M}\right)^8 \left(\frac{10^{-16}\mathrm{eV}}{\mu}\right)^9 \text{ seconds}$$

Wonderful sources of GWs

Brito, Cardoso, Pani, Lecture Notes Physics 971 (2020)

Bounding the boson mass with EM observations

Pani + PRL109, 131102 (2012)



Bound on photon mass is model-dependent: details of accretion disks or intergalactic matter are important… but gravitons interact very weakly!

$$m_g < 5 \times 10^{-23}\,\mathrm{eV}$$

Brito + PRD88:023514 (2013); Review of Particle Physics 2014

Wonderful sources for different GW-detectors

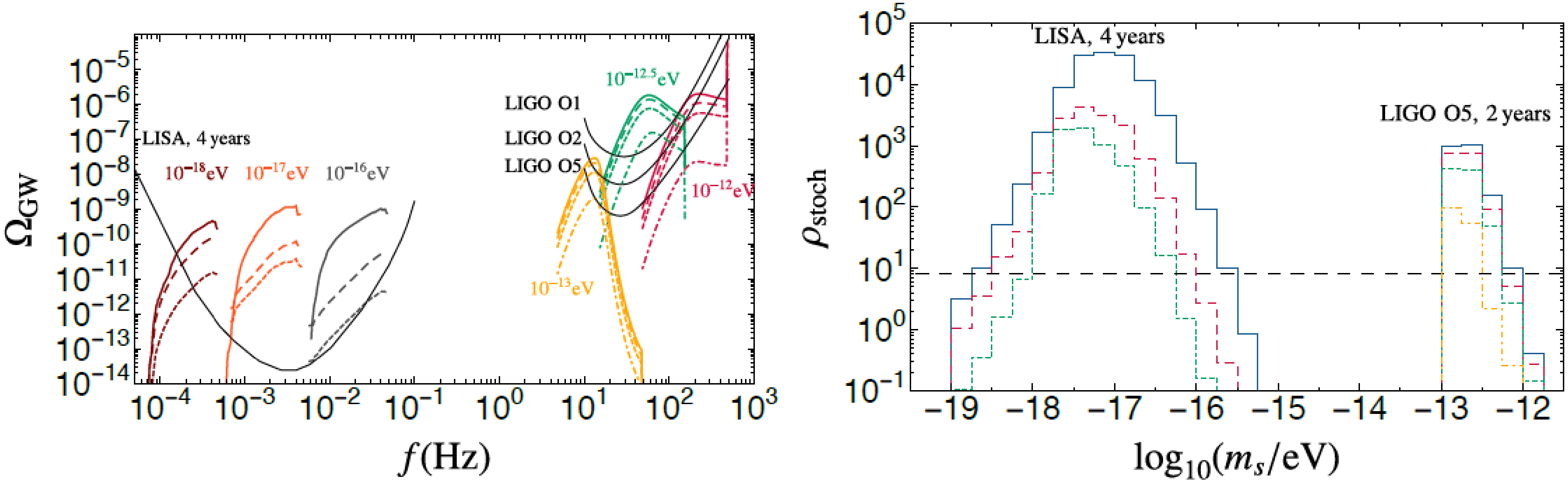
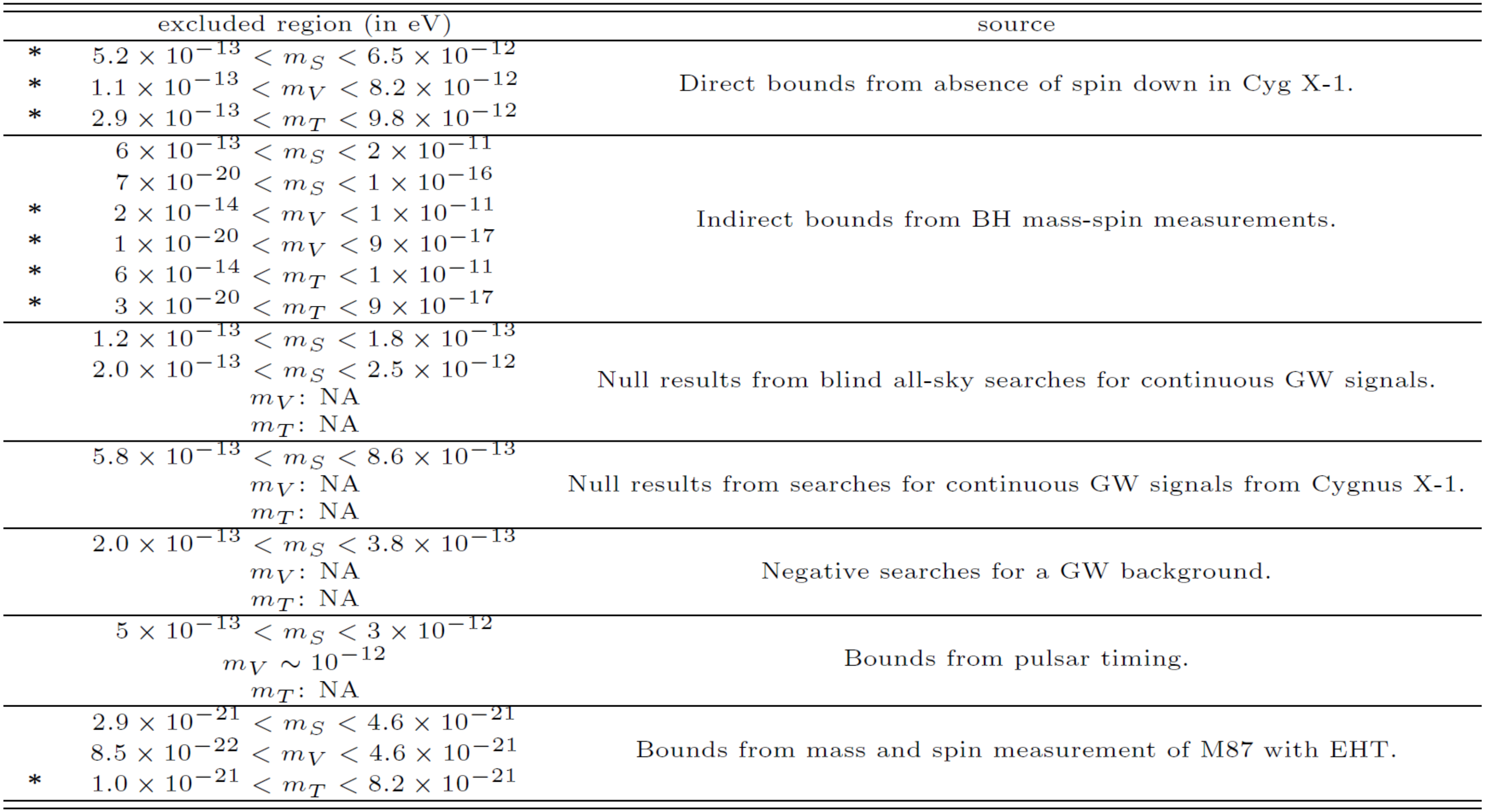


FIG. 2. Left panel: stochastic background in the LIGO and LISA bands. For LISA, the three different signals correspond to the "optimistic" (top), "less optimistic" (middle) and "pessimistic" (bottom) astrophysical models. For LIGO, the different spectra for each scalar field mass correspond to a uniform spin distribution with (from top to bottom) $\chi_i \in [0.8, 1]$, $[0.5, 1]$, $[0, 1]$ and $[0, 0.5]$. The black lines are the power-law integrated curves of Ref. [61], computed using noise PSDs for LISA [9], LIGO's first two observing runs (O1 and O2), and LIGO at design sensitivity (O5) [62]. By definition, $\rho_{\rm stoch} \geq 1$ when a power-law spectrum intersects one of the power-law integrated curves. Right panel: $\rho_{\rm stoch}$ for the backgrounds shown in the left panel. We assumed $T_{\rm obs} = 2\,{\rm yr}$ for LIGO and $T_{\rm obs} = 4\,{\rm yr}$ for LISA.

Scalars: Brito + PRL119: 131101 (2017); arXiv 1706:05097; For vectors: Tsukada + arXiv: 2011.06995

Constraints on fundamental fields via superradiance

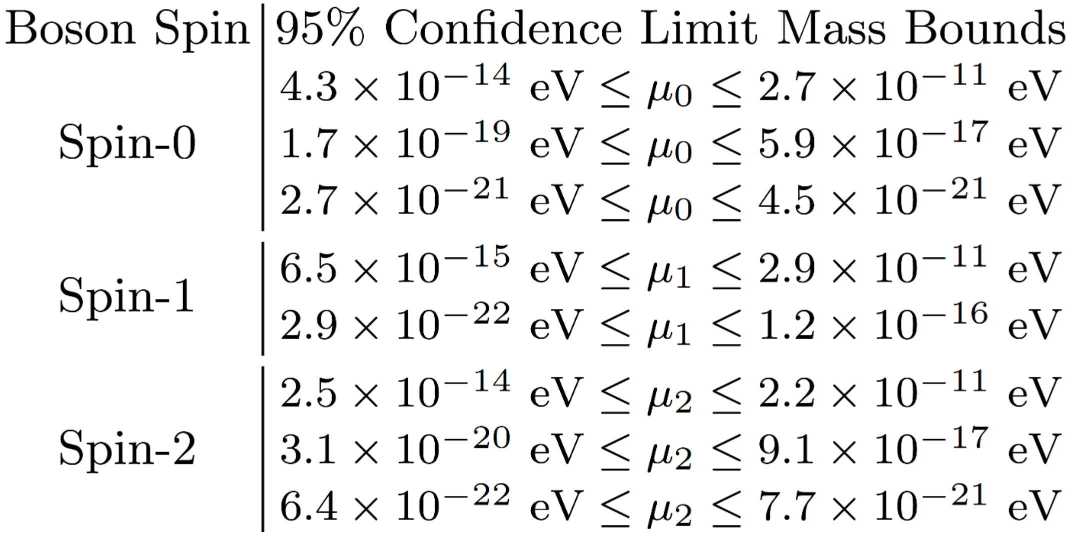


	excluded region (in eV)	source
*	$5.2\times10^{-13} < m_S < 6.5\times10^{-12}$	Direct bounds from absence of spin down in Cyg X-1.
*	$1.1\times10^{-13} < m_V < 8.2\times10^{-12}$	
*	$2.9\times10^{-13} < m_T < 9.8\times10^{-12}$	
	$6\times10^{-13} < m_S < 2\times10^{-11}$	Indirect bounds from BH mass-spin measurements.
	$7\times10^{-20} < m_S < 1\times10^{-16}$	
*	$2\times10^{-14} < m_V < 1\times10^{-11}$	
*	$1\times10^{-20} < m_V < 9\times10^{-17}$	
*	$6\times10^{-14} < m_T < 1\times10^{-11}$	
*	$3\times10^{-20} < m_T < 9\times10^{-17}$	
	$1.2\times10^{-13} < m_S < 1.8\times10^{-13}$	Null results from blind all-sky searches for continuous GW signals.
	$2.0\times10^{-13} < m_S < 2.5\times10^{-12}$	
	m_V: NA	
	m_T: NA	
	$5.8\times10^{-13} < m_S < 8.6\times10^{-13}$	Null results from searches for continuous GW signals from Cygnus X-1.
	m_V: NA	
	m_T: NA	
	$2.0\times10^{-13} < m_S < 3.8\times10^{-13}$	Negative searches for a GW background.
	m_V: NA	
	m_T: NA	
	$5\times10^{-13} < m_S < 3\times10^{-12}$	Bounds from pulsar timing.
	$m_V \sim 10^{-12}$	
	m_T: NA	
	$2.9\times10^{-21} < m_S < 4.6\times10^{-21}$	Bounds from mass and spin measurement of M87 with EHT.
	$8.5\times10^{-22} < m_V < 4.6\times10^{-21}$	
*	$1.0\times10^{-21} < m_T < 8.2\times10^{-21}$	

Brito, Cardoso & Pani Lecture Notes Physics 971 (2020)
https://centra.tecnico.ulisboa.pt/network/grit/files/superradiantbounds/

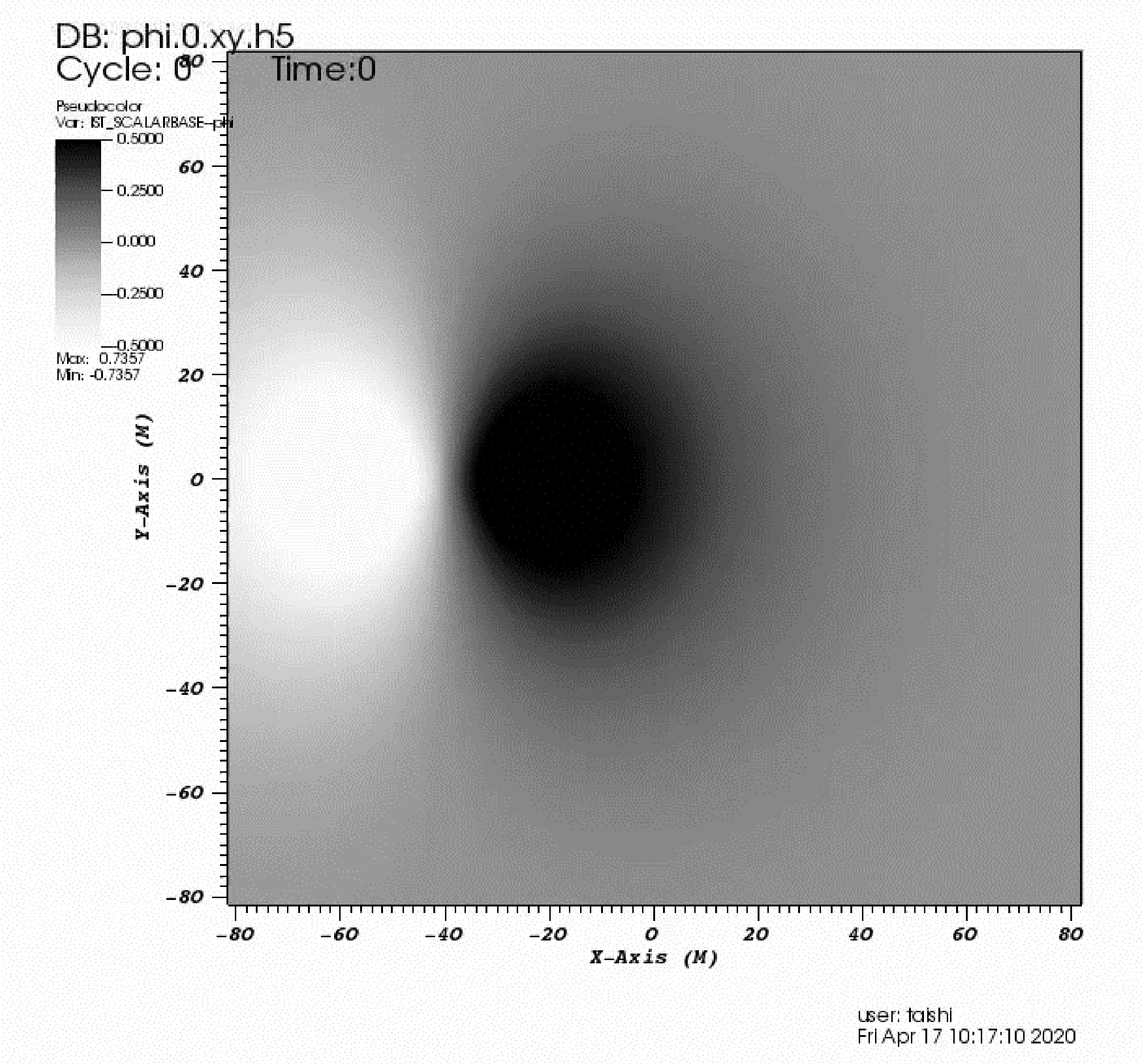
Constraints on fundamental fields via superradiance

M. Stott arXiv:2009.07206



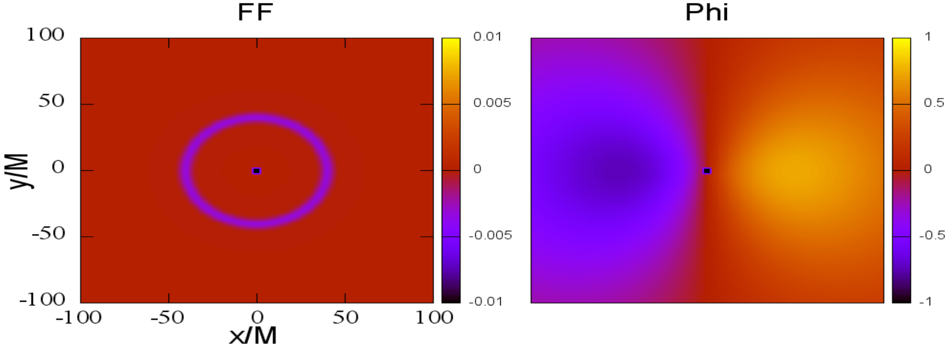
Boson Spin	95% Confidence Limit Mass Bounds
Spin-0	4.3×10^{-14} eV $\leq \mu_0 \leq 2.7 \times 10^{-11}$ eV
	1.7×10^{-19} eV $\leq \mu_0 \leq 5.9 \times 10^{-17}$ eV
	2.7×10^{-21} eV $\leq \mu_0 \leq 4.5 \times 10^{-21}$ eV
Spin-1	6.5×10^{-15} eV $\leq \mu_1 \leq 2.9 \times 10^{-11}$ eV
	2.9×10^{-22} eV $\leq \mu_1 \leq 1.2 \times 10^{-16}$ eV
Spin-2	2.5×10^{-14} eV $\leq \mu_2 \leq 2.2 \times 10^{-11}$ eV
	3.1×10^{-20} eV $\leq \mu_2 \leq 9.1 \times 10^{-17}$ eV
	6.4×10^{-22} eV $\leq \mu_2 \leq 7.7 \times 10^{-21}$ eV

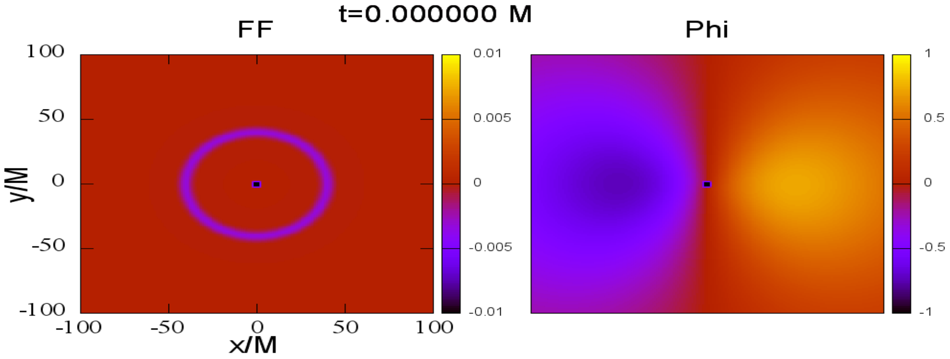
Tidal effects



Baumann+ PRD99:044001 (2019); Cardoso + PRD101:064054 (2020)

$$\mathcal{L} = \frac{R}{k} - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{2}g^{\mu\nu}\partial_\mu\Psi\partial_\nu\Psi - \frac{\mu_{\rm S}^2}{2}\Psi\Psi - \frac{k_{\rm axion}}{2}\Psi\,{}^*F^{\mu\nu}F_{\mu\nu}$$

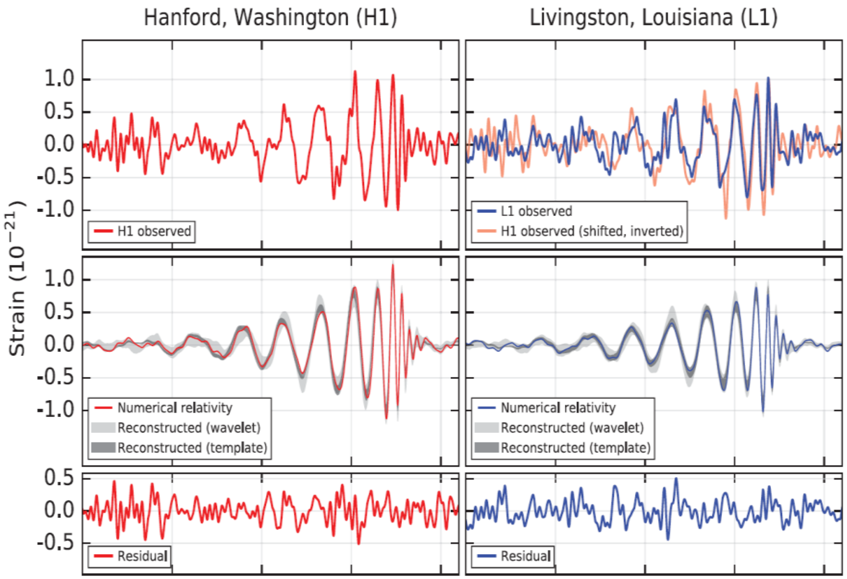




Ikeda + PRL122: 081101 (2019)

Boskovic+ PRD99: 035006 (2019)

The nature of dark compact objects



$$f_{GW}^{-8/3}(t) = \frac{(8\pi)^{8/3}}{5}\left(\frac{G\mathcal{M}}{c^3}\right)^{5/3}(t_0 - t)$$

$$\mathcal{M} = (\mu^3 M^2)^{1/5}$$

Two unknowns, need frequency at two instants. Result: M ~ 65 suns

Use Kepler's law, separation at collision is ~ 500 Km… same using ringdown…

Massive, compact object indeed!

Why is this enough?

BHs are end-point of gravitational collapse, using EoS thought to prevail.

No other massive, dark object has been seen to arise from collapse of known matter.

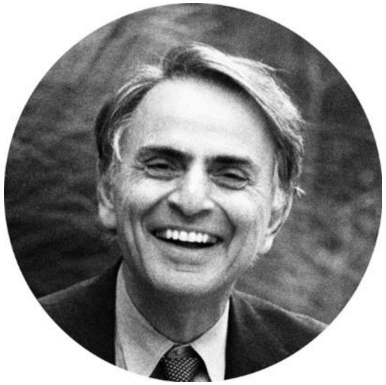
Why is this not enough?

Cardoso & Pani, Living Reviews in Relativity (2019)

1. BH exterior is pathology-free, interior is not.

2. Quantum effects not fully understood. Non-locality to solve information paradox? Is BH just a fuzzball? BH area quantization? (Mathur 2005; Bekenstein & Mukhanov 1995; Giddings 2017)

3. Tacitly assumed quantum effects at Planck scales. Planck scale could be significantly lower *(Arkani-Hamed+ 1998; Giddings & Thomas 2002)*. Even if not, many orders of magnitude standing, surprises can hide.



"Extraordinary claims require extraordinary evidence."
Carl Sagan

4. Dark matter exists, and interacts gravitationally. Are there compact DM clumps?

5. Physics is experimental science. We can test exterior. Aim to quantify evidence for horizons. Similar to quantifying equivalence principle.

Some challenges

Cardoso & Pani, Living Reviews in Relativity 22: 1 (2019)

i. Well-posed alternatives yielding ultracompact solutions?

ii. Formation mechanism for alternatives?

iii. Are these BH mimickers dynamically stable? Timescales?

iv. How do they look like? Is GW or EM signal similar to BHs?

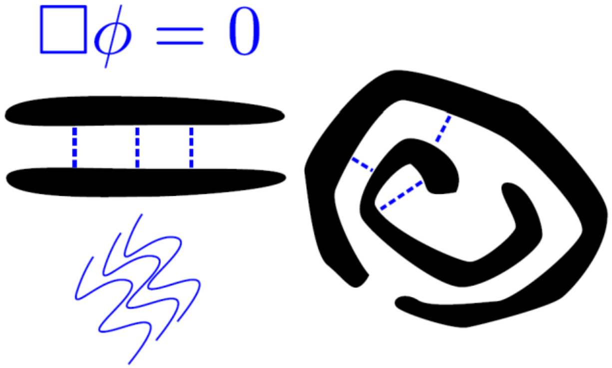
v. Observationally, how close do we get to horizons?

IIIb. Stability of objects with photospheres

Static objects: *No uniform decay estimate with faster than logarithmic decay can hold for axial perturbations of ultracompact objects.*

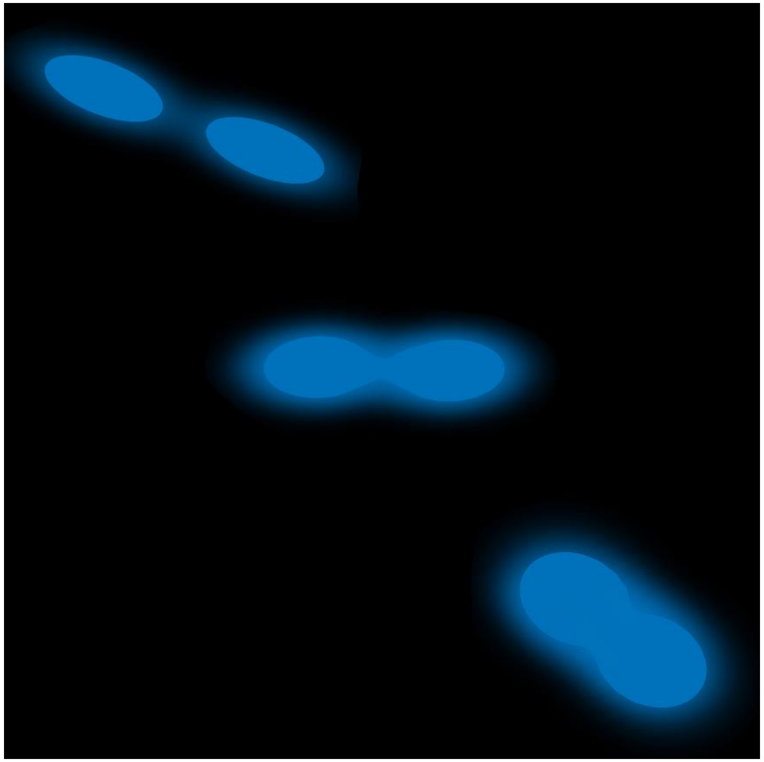
Keir CQG33: 135009 (2016); Cardoso + PRD90:044069 (2014)

$$\mathcal{E}^{(N)}_{\mathrm{local}}(t) \lesssim \frac{1}{(\log(2+t))^2}\mathcal{E}^{(N)}_{(2)}(0)$$



Burq, Acta Mathematica 180: 1 (1998)

GW signal: inspiral



Nature of inspiralling objects is encoded

(i) in way they respond to own field (multipolar structure)

(ii) in way they respond when acted upon by external field of companion – through their tidal Love numbers (TLNs), and

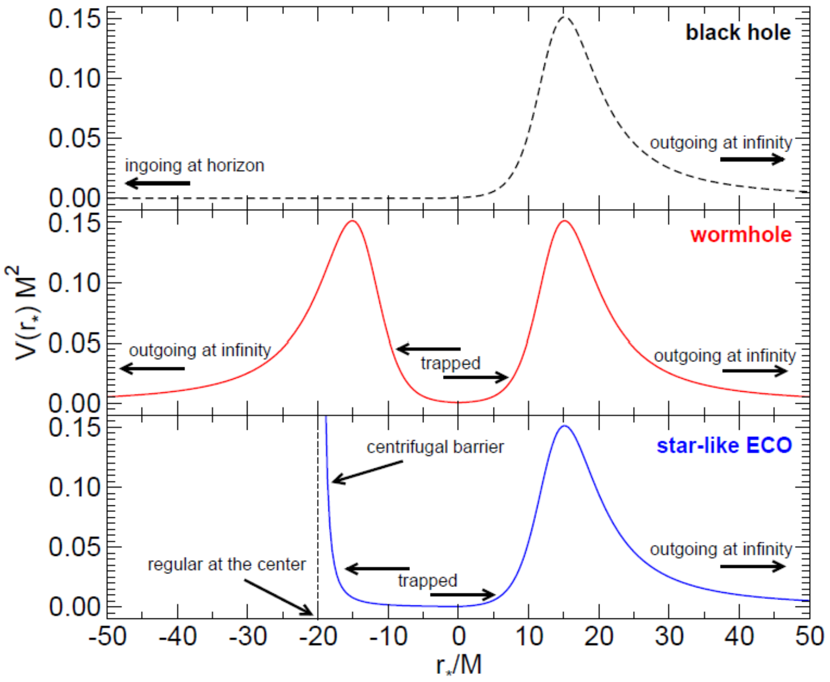
(iii) on amount of radiation absorbed, i.e., tidal heating

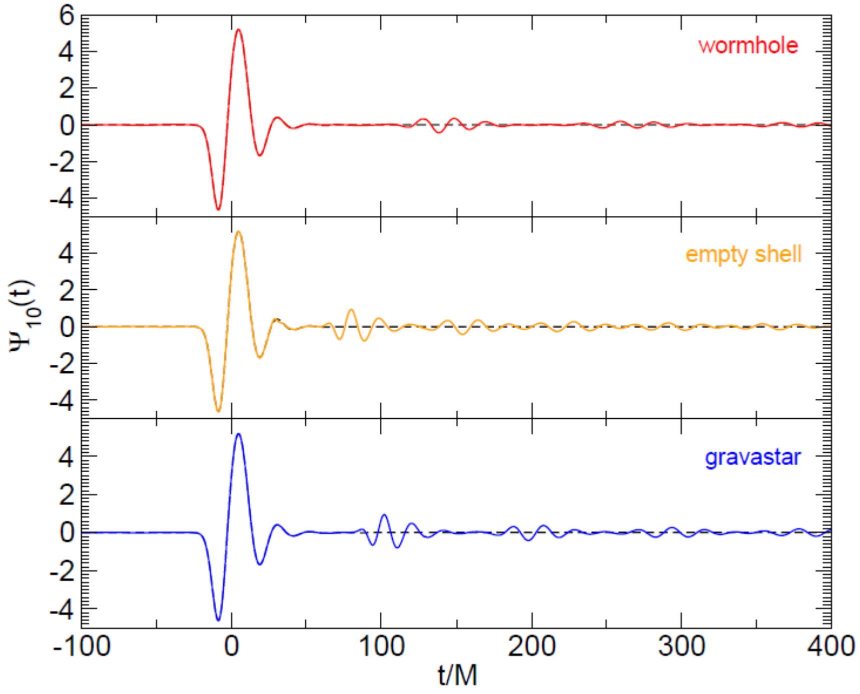
$$\tilde{h}(f) = \mathcal{A}(f)e^{i(\psi_{\rm PP}+\psi_{\rm TH}+\psi_{\rm TD})}$$

Cardoso + PRD95:084014 (2017); Sennett + PRD96:024002 (2017)
Maselli+ PRL120:081101 (2018); Cardoso & Pani, Nature Astronomy 1:586 (2017)

Post-merger: echoes

more than just w-modes





Cardoso + PRL116:171101 (2016); Cardoso and Pani, Nature Astronomy 1: 2017
Cardoso and Pani, Living Reviews in Relativity 22:1 (2019)

Searches for echoes were conducted by the LIGO/Virgo Collaboration arXiv:2010:14529

Surprises?

Bekenstein & Mukhanov 1995
Kleban+2019; Cardoso+ 2019; Agullo+ arXiv:2007.03700

i. Postulate some area quantization

$$A = \alpha l_P^2 N = \alpha \frac{\hbar G}{c^2} N$$

$$\Delta A = \alpha \frac{\hbar G}{c^3} \Delta N = 32\pi \frac{G^2}{c^4} M \Delta M$$

ii. Compute absorbed energy of graviton

$$\Delta M = \alpha \frac{c\hbar}{32\pi G} \frac{\Delta N}{M}$$

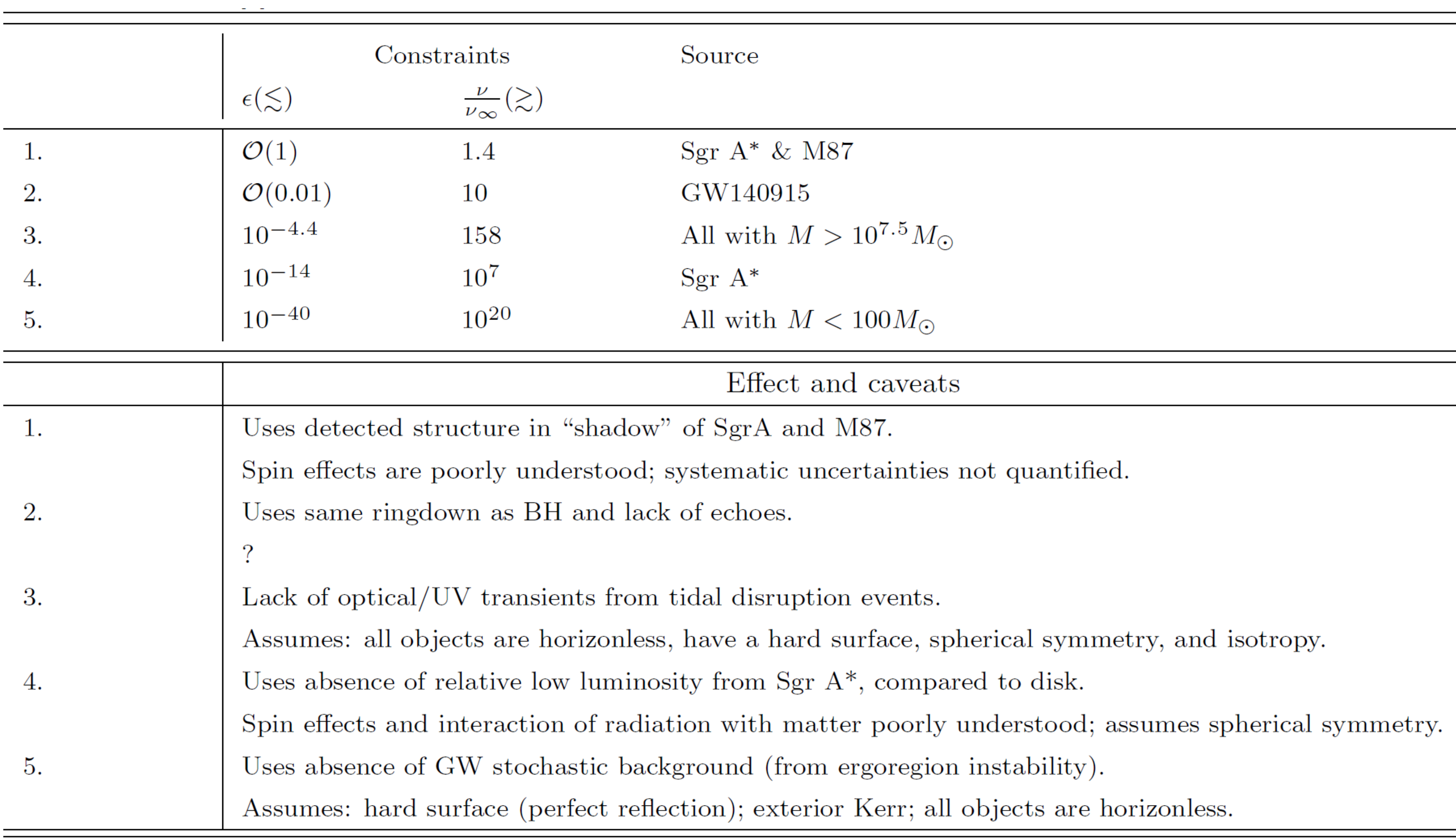
$$\omega_n = \frac{\Delta M c^2}{\hbar} = \frac{n\alpha}{32\pi} \frac{c^3}{MG}$$

Classical! Consequences for ringdown, TLNs, tidal heating

Agullo + arXiv:2007.03700
Brustein & Sherf arXiv:2008.02738

v. The evidence for black holes

Cardoso and Pani, Living Reviews in Relativity *(2019)*



	Constraints		Source
	$\epsilon(\lesssim)$	$\frac{\nu}{\nu_\infty}(\gtrsim)$	
1.	$\mathcal{O}(1)$	1.4	Sgr A* & M87
2.	$\mathcal{O}(0.01)$	10	GW140915
3.	$10^{-4.4}$	158	All with $M > 10^{7.5} M_\odot$
4.	10^{-14}	10^{7}	Sgr A*
5.	10^{-40}	10^{20}	All with $M < 100 M_\odot$

	Effect and caveats
1.	Uses detected structure in “shadow” of SgrA and M87. Spin effects are poorly understood; systematic uncertainties not quantified.
2.	Uses same ringdown as BH and lack of echoes. ?
3.	Lack of optical/UV transients from tidal disruption events. Assumes: all objects are horizonless, have a hard surface, spherical symmetry, and isotropy.
4.	Uses absence of relative low luminosity from Sgr A*, compared to disk. Spin effects and interaction of radiation with matter poorly understood; assumes spherical symmetry.
5.	Uses absence of GW stochastic background (from ergoregion instability). Assumes: hard surface (perfect reflection); exterior Kerr; all objects are horizonless.

Conclusions: exciting times!

Gravitational wave astronomy *will* become a precision discipline, mapping compact objects throughout the entire visible universe.

Black holes remain the most outstanding object in the universe. BH spectroscopy will allow to test GR and provide strong evidence for the presence of horizons… improved sensitivity pushes putative surface closer to horizon, like probing short-distance structure with accelerators. BHs can play the role of perfect laboratories for particle physics, or high energy physics.

> “But a confirmation of the metric of the Kerr spacetime (or some aspect of it) cannot even be contemplated in the foreseeable future.”
>
> *S. Chandrasekhar, The Karl Schwarzschild Lecture, Astronomischen Gesellschaft, Hamburg, 18 Sept. 1986*

Thank you